

IMPROVEMENT OF NONLINEAR SIMULATION USING PARAMETER ESTIMATION TECHNIQUES

Philipp Krämer^a, Bernard Gimonet^b

^a Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

^b Office National d'Etudes et de Recherches Aéronautiques (ONERA)

Abstract

The need for increased fidelity and performance in helicopter flight simulation requires new concepts in model generation and simulation.

One approach consists of combining generic nonlinear modeling with reduced order parameterized terms. It is intended to systematically integrate this new technique into existing model structures as a complementary way of generating and processing flight dynamics models which combine physical accuracy and wide ranges of validity with reduced numerical workload and computation time.

As an exemplary application, the *parametric wake distortion* model is being investigated and optimized using Bo105 flight test data.

The paper describes the approach of the DLR Institute of Flight Research which utilizes a parameter optimization routine that has been integrated into the common simulation environment HOST by the ONERA Department of Systems Control and Flight Dynamics.

Symbols

c_0, c_l, c_m	thrust, roll, pitch moment coefficient, [-]
p, q, r	roll, pitch, yaw rate, [rad/sec]
\underline{p}	parameter vector
$\hat{\underline{p}}$	estimated parameter vector
t	time, [sec]
t_n	observation time, [sec]
$\underline{x}, \underline{u}, \underline{y}$	state, input, output variables
\underline{y}_{mes}	measurements

J	cost function, [-]
K_p, K_q	wake distortion parameter roll, pitch, [-]
K_R	wake distortion parameter hover, [-]
$\hat{\underline{L}}$	gain matrix, [sec/m]
\underline{M}	apparent mass matrix, [-]
R	covariance error of measurements
β	blade flapping angle, [rad]
δ_x, δ_y	longitudinal, lateral cyclic stick input, [%]
λ	inflow ratio, [-]
θ_{1s}, θ_{1c}	longitudinal, lateral cyclic blade pitch, [rad]
Ω	main rotor RPM, [rad/sec]
$\nabla J, \nabla_2 J$	first and second gradient matrices
$\dots 0, c, s$	mean, cosine and sine component
ACT/FHS	Active Control Technology / Flying Helicopter Simulator
$FADEC$	Full Authority Digital Engine Control
$HOST$	Helicopter Overall Simulation Tool
PID	Parameter Identification
RPM	Revolutions Per Minute
SEE	Système d'Exploitation d'Essais (Test Evaluation System Interface)

1 Introduction

In most of the current rotorcraft flight research projects are two major points where accurate flight simulation is crucial.

On one hand, the support of flight testing represents one large area of flight simulation application. On the other hand, pilot training sets the mark for helicopter simulator accuracy standardization.

Flight test support is even more relevant when new concepts, such as control systems or control laws, are be-

Presented at the 26th European Rotorcraft Forum, The Hague, The Netherlands, 26-29 September 2000.

© 2000 by the Netherlands Association of Aeronautical Engineers NVvL.

ing investigated. Here, simulator trials before actual flight are vital both for security and economic reasons. This field comprises also preparatory work for in-flight simulation that will be conducted by the DLR Institute of Flight Research on its EC135 ACT/FHS testbed. For this case, high bandwidth system models are mandatory for the design of the Model Following Control System [1, 2].

Helicopter training simulators are standardized e.g. by the Advisory Circular AC 120-63 on Helicopter Simulator Qualification from 1994, published by the US Federal Aviation Authority (FAA), and the European counterpart, the Joint Aviation Requirement JAR-STD 1H, on Helicopter Flight Simulators released in 1999 by the Joint Aviation Authorities (JAA).

These requirements for higher accuracies lead to an extended use of nonlinear generically derived models in helicopter flight simulation. However, the complexity of modeling is limited by the demand for real-time capabilities of piloted simulations. Therefore, a solution has to be found, where high fidelity is combined with a feasible requirement of computation time.

Recent research led to the combination of nonlinear modeling with parametric modeling approaches. These newly defined parameterized models can be subject to a parameter optimization procedure to adapt the model response to flight test data.

The HOST (Helicopter Overall Simulation Tool) system has been chosen as the simulation environment for this research. HOST is the comprehensive simulation code developed by Eurocopter which is now the common flight dynamics research tool in use by Eurocopter, Eurocopter Deutschland GmbH, DLR and ONERA.

A highly efficient parameter identification routine has been integrated (see Section 4) and was used for the described work. To obtain a well-conditioned problem with correct sensitivity about all parameters, it is generally necessary to fit measurements and simulation results on several concatenated runs. This aims towards an estimation of parameters that are valid for several flight conditions as well as to estimate parameters of 'Multiple Input-Multiple Output' (MIMO) problems, such as cross coupling.

To have a non-trivial application case, a parametric wake distortion (PWD) model [3, 4, 5, 6] has been chosen to get experience for the necessary functionality and the optimal way of implementation.

After this introduction to background and intentions of the described research, the modeling approach and some thoughts on the optimization of these models are presented.

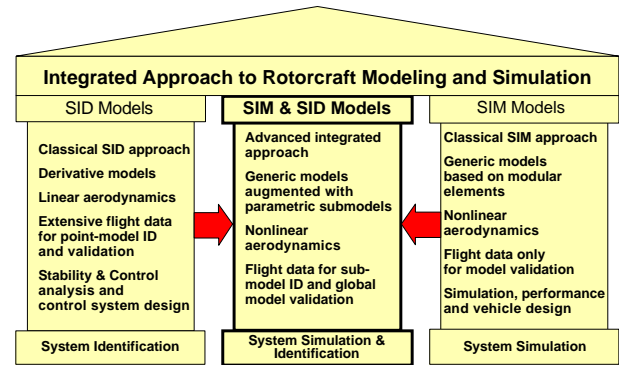


Figure 1: Three columns model [7].

The applied models are discussed with special emphasis on model architecture. The parameter identification routine and its connection to the simulation tool is then described as a central point of the performed work since the decisions made in the development process of these tools have direct influence on the system performance and thus on the quality of the identified models. Selected results demonstrate the potential of adapting specialized models and a high performance identification routine in optimizing the HOST simulation fidelity.

2 Approach and Optimization

One approach by the DLR Institute of Flight Research to integrate parameterized models into a nonlinear environment is illustrated in Figure 1 [7].

It refers to a combination of the advantages of two fundamentally different approaches in the development of flight dynamics models. First, linear derivative modeling that is to be identified from flight test data, represented by the left column. This technique generates models that are accurate but subject to small perturbation assumptions and a restricted representation of the physics (see [8] for examples). The second approach uses detailed vehicle information to develop generic nonlinear helicopter models, represented by the right column. Recent research led to significant improvements of these models so that the standards can be mostly fulfilled [5]. The disadvantage of this technique is that the model complexity is limited by the required computational speed.

To combine the advantages of these approaches more sophisticated nonlinear modeling approaches are being extended with models that are subject to model reduction procedures. These models are of lower order than the original fully nonlinear models and have certain physical sys-

tem properties represented in parametric terms. Furthermore, phenomena on which not enough physical knowledge is available can be represented by parameterized models. The models are set up from phenomenological observations to comprise additional degrees of freedom and are suitable for pilot-in-the-loop real time applications. This third approach is represented by the middle column in Figure 1. As an example for rotor modeling, this technique allows the description of local rotor dynamics with a global parametric approach which is fed back to the rotor's blade element equations.

The approach suggests the use of optimization techniques to tune the parameters inside the models and thus to improve the simulation result. This is realized as a connection between identification and simulation tools.

It is evident that wherever parametric modeling is applied, a step back from physical authenticity is being made. The disadvantages are clear. The optimization of models by means of parameter identification tends to correct any kind of errors. This also comprises errors of deficiencies that are not within the scope of the specific problem that is being analyzed.

The reasons, why it is still beneficial to use such combined techniques are almost as clear, though. It promises to improve simulation fidelity to a level that would require far more complex models — and thus increased computational time — if modeled with generic nonlinear methods. The threat of affecting other than the model incapacities aimed for can be reduced by using models that are embedded deeply in the model structure in a way that they only influence the local dynamics.

3 Nonlinear Modeling

One of the methods to derive parameterized models from complex nonlinear systems is to perform a model reduction procedure. With the use of e.g. transfer functions or differential equation systems, the number of state variables is being reduced and the physical information is represented by the remaining state variables or the generated model parameters, respectively. In some cases, this method generates linear systems which then can be extended e.g. by time delays if the linear representation is not satisfying the demands.

A more complex approach would not be convenient since a model setup from this basis would quickly lead to highly complex models and the advantage in processing time would decrease.

As indicated above, the chosen solution could be the combination of a generically derived model with an approximated parametric extension. In the effort towards a systematical usage of parameter identification techniques inside a nonlinear environment, a model of this kind is used to develop initial experiences in this domain of research which is described in the following.

3.1 Parametric Wake Distortion

With a first test case it was possible to validate the parameter estimation tool in its function. This test case was the optimization of a 'Single Input-Single Output' (SISO) model with well known parameter sensitivity. The system proved to run correctly and to optimize the assigned parameters within reasonable time. Until that stage, the tool has not been tested for the optimization of multiple parameters but the basic capabilities have been embedded in the programming of the procedure.

After this basic verification a more sophisticated model was to be processed to analyze the system's capability to cope with more deeply embedded parameterized models. Due to its significance the parametric wake distortion model based on the work on helicopter wake modeling by Rosen [3], Keller and Curtiss [4] and Basset [6] has been chosen. Primarily, the wake distortion theory points towards an explanation of the still existing deficiencies in predicting the cross coupling of a helicopter. It combines a state-of-the-art rotor wake model with parametric architecture and therefore it is a very adequate object of investigation.

$$\underline{M} \begin{bmatrix} \dot{\lambda}_0 \\ \dot{\lambda}_s \\ \dot{\lambda}_c \end{bmatrix} + \hat{\underline{L}}^{-1} \begin{bmatrix} \lambda_0 \\ \lambda_s \\ \lambda_c \end{bmatrix} = \begin{bmatrix} c_0 \\ c_l \\ c_m \end{bmatrix} + \frac{1}{\Omega} \hat{\underline{L}}^{-1} \begin{bmatrix} 0 \\ K_p(p - \dot{\beta}_s) \\ K_q(q - \dot{\beta}_c) \end{bmatrix} \quad (1)$$

As can be seen from Equation 1 the model refers to the Pitt and Peters dynamic wake approach [9] which is widely used for rotor inflow computation. As introduced in [5], the term on the right hand side represents the feedback of the tip path plane dynamics onto the induced velocities of the main rotor, magnified by the two parameters K_p and K_q . For validation purposes, this model gives also the possibility to test the optimization code with more than one parameter to identify. The formulation of the problem, comparable to a feedback control structure, leads to a non-trivial problem incorporating correlation aspects.

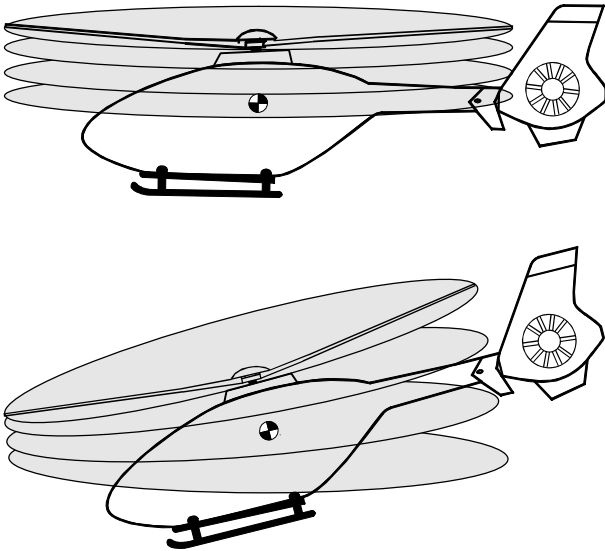


Figure 2: Wake propagation of a pitching helicopter.

As denoted in [6], the original Pitt and Peters formulation showed remarkable improvements in the prediction of cross coupling in forward flight but was insufficient near hover.

The basic theory is that in a state near hover, when the helicopter is performing a steady rotational movement, the effect of the blade vortices being compressed under one side of the rotor (see Figure 2) would lead to an induction to the global wake field. This results in the distortion of the rotor wake which counter-reacts with the helicopter movement.

According to theory, the rotational movement affects the distribution of tip vortices emitted by the rotor. This, having a direct effect on the induced velocity field has also an impact on the resulting air loads. The gyroscopic behavior of the rotor is then the reason for the off-axis response of the aircraft.

As horizontal speed increases, the vortices are dragged out of the zone of influence of the main rotor and the effect diminishes. Therefore, the wake distortion parameters can be assumed to approximate zero with increasing horizontal speed.

It was shown that in hover, the wake distortion parameters coincide at a value denoted K_R by Keller [10]. Several approaches with different strategies have been undertaken to derive its numerical value. Table 1 shows that the value for K_R falls in a region between approximately 0.5 and 2 but is equally scattered within this band. This variation is due to the different models that have been used and other circumstances of the analysis.

Among other dependencies described in [6] the effect of forward speed on the wake distortion parameters has

Reference	Model	K_R
Rosen, Isser [3]	Prescribed wake	0.75
Keller [10]	Spiral vortex tube	1.5
Basset [11]	Spiral vortex ring	1.5
Barocela, Peters et al. [12]	Momentum	0.5
	Prescribed Wake	1.0
Bagai, Leishman et al. [13]	Free Wake	1.75

Table 1: Wake distortion coefficients in hover.

been paid special attention to during this analysis in terms of optimized response.

3.2 Component Models

The example described above is a very convenient case for the kind of study aimed for i.e. the optimization of generically set up parametric models. The model includes parameters that have been derived from physical observations and not from e.g. a polynomial function with the predefined purpose to be optimized to fit measured data.

To give an example of further possible applications of this method, two problems might be indicated that represent different approaches of parametric modeling. The improvement of the Fenestron dynamics model and the identification of an engine model.

The approach of optimizing models in a comprehensive generic environment comprises the improvement of models that suffer from substantial deficiencies. These models can be extended by parametric terms that, after undergoing the optimization procedure, represent the error of the *bare* model. The formulation of the Fenestron dynamics which is also a requirement for the ACT/FHS (EC135) system simulation may be named as an example for this case. Here again, it is crucial to figure out carefully what kind of errors the identification procedure is dealing with.

Models that already exist in parametric form are a natural point of interest of the described techniques. Engine modeling can be named as an example of modeling where the model is being reduced to its significant dynamic properties by means of parameterization [14]. It is intended to verify the new system's capability for this case, too.

4 Integration of Parameter Estimation into the HOST Tool

The HOST software structure is designed to support the integration of various models, despite of their levels of complexity. The description of the local sub models and

their links is made into data files and processed by building subroutines. The use of HOST proceeds in an interactive way. At each step, a dialog is established with the user by interfaces such as interactive menus, data acquisitions or modifications and graphic displays on the screen. It has been decided to introduce a parameter identification functionality to HOST in order to provide an interactive tool able to improve the non linear simulations.

4.1 HOST Description

For precise description see the collection of HOST documents [15] as well as [16] for descriptions on the application of the system. We just intend to describe its main functionalities and their interest for parametric identification (PID).

The standard HOST version produces:

- Equilibrium definition and trim calculation.
- Equilibrium scanning versus parameter sweeps.
Routines able to add a model parameter into a list and to modify its value can also provide an easy possibility to obtain parameter dependent simulations for identification procedures.
- Simulations of helicopter behavior driven by control inputs from a flight test data set (*SEE* format) to compare measured response with simulated response.
The selection of *SEE*-files, simulation time ranges, control inputs and outputs is obtained from interactive inputs to menus. The simulation results can be compared with flight data for selected inputs and both data sets can be plotted simultaneously.
- Inverse simulation to provide desired variations on observation outputs by calculating helicopter input.
Among the code used for inverse simulation are several tools that are of use for PID development, such as the selection routine for the chosen outputs. The selected outputs for inverse simulation will be used to compute the fitting criterion.
- Graphic display of results.

These HOST functions will be used with few modifications to build the parameter estimation extension of the present code organized in a structure of hierarchical directories.

4.2 Parameter Identification

The choice of a tuning technique may have some consequences for the connection of HOST with the parameter identification codes. It is very important to choose an algorithm needing as few iterations as possible, even for a large number of parameters, using the particular structure of the fitting criterion. For that reason, the output error minimization technique [17] with the second order Newton-Raphson procedure has been chosen.

Let us describe the model by the following equations:

$$\begin{cases} \dot{\underline{x}} &= f(\underline{x}, \underline{u}, \underline{p}) \\ \underline{y}(t_n) &= g(\underline{x}(t_n), \underline{u}(t_n), \underline{p}) = \underline{y}(n) \end{cases} \quad (2)$$

The cost function to be minimized by the estimator is:

$$J = \frac{1}{2} \sum_{n=0}^{N-1} [\underline{y}(n) - \underline{y}_{mes}(n)]^T R^{-1} [\underline{y}(n) - \underline{y}_{mes}(n)] \quad (3)$$

The estimated parameters are obtained iteratively from the gradient of the criterion ∇J and an approximation of the second gradient $\nabla_2 J$. At the end of iteration k , the estimated vector parameter is $\hat{\underline{p}}(k)$. The estimated parameter vector at iteration $k + 1$ is then obtained by:

$$\hat{\underline{p}}(k + 1) = \hat{\underline{p}}(k) - [\nabla_2 J]^{-1} \nabla J \quad (4)$$

The gradients are issued from the sensitivity functions $\left[\frac{\partial \underline{y}(n)}{\partial \underline{p}^{(i)}} \right]$ which can be computed from the nominal simulation and the perturbed simulations:

$$\begin{cases} \dot{\underline{x}} &= f(\underline{x}, \underline{u}, \underline{p}^{(i)}) \\ \underline{y}(n) &= g(\underline{x}(t_n), \underline{u}(t_n), \underline{p}^{(i)}) \\ \dot{\underline{x}}_i &= f(\underline{x}_i, \underline{u}, \underline{p}^{(i)} + \Delta \underline{p}^{(i)}) \\ \underline{y}_i(n) &= g(\underline{x}_i(t_n), \underline{u}(t_n), \underline{p}^{(i)} + \Delta \underline{p}^{(i)}) \end{cases}$$

by

$$\left[\frac{\partial \underline{y}(n)}{\partial \underline{p}^{(i)}} \right] = \frac{\underline{y}_i(n) - \underline{y}(n)}{\Delta \underline{p}^{(i)}} \quad (5)$$

As shown in [18], at time t_n all the outputs of the perturbed simulations are needed. In HOST this will imply the management of so called parallel simulations in order to get all the needed information at time t_n without any unnecessary storage. This constraint is related to the choice of the Newton-Raphson procedure. It would not

be the case using the conjugate gradients technique to be tested in the near future.

4.3 Integration of HOST and Parameter Identification

4.3.1 Software Requirements

An integration scheme is necessary all along the time range selected for optimization and simulation, but also for several runs generally necessary to provide enough information to tune the selected parameters. This is not available in the standard HOST code and has to be introduced. The connection must satisfy some constraints considering the organization of menus and parameter selection to maintain a low workload for users.

1. The identification procedure is activated from a button in the *Secondary Menu*, it opens several connected sub-menus to select parameters, inputs, outputs, SEE-files, number of iterations, ...
2. The trim conditions defined at the beginning of the HOST session for any standard processing can also be modified in the identification menu and it is not necessary to go back to process successive parameter estimations with various computing conditions.
3. The selection procedure is copied from the HOST one but all the individual selections are available separately from individual buttons in the identification menu and they are processed by specialized subroutines.

New FORTRAN subroutines are stored in a new PID source code directory. Some FORTRAN subroutines of the standard version have to be modified. Interference with the actions of a standard HOST user must be avoided, following some simple rules.

- A common file is never modified or extended, new commons have just to be introduced in the proper include directory.
- A small number of routines are modified with a logic flag avoiding modification when the parameter identification option is not running.
- The general organization of the code and the conventional names are respected.

- All new routines are introduced in the new source directory. The names of these routines are chosen in a way that it is possible to directly allocate them to the PID functionality.

Most of the new created routines are copied from standard HOST ones, but often split into individual selection procedures: inputs, outputs, etc. So it will be possible to process successive identifications with few interactions with the *Parameter Identification Menu* (see Figure 3).

4.3.2 Organization of the Integration Calculus

The choice of the interactive HOST code and the output error minimization technique for parameter identification has some consequences on the connection.

1. The separated roles devoted to HOST and PID are defined as below.

HOST	defines	- the structure of the model.
	manages	- the list of tunable parameters. - the files containing the flight test data.
	provides	- the simulation.
PID	computes	- the fitting criteria. - the proposed variation of parameters at each step.

So the PID program is more or less reduced to its optimization part.

2. The Newton-Raphson procedure used in the estimation procedure implies parallel simulations of nominal and perturbed models as explained above. The classical simulation in HOST supposed to deliver the output model for the criterion and gradients calculations has to be modified according the following scheme:

- Time t : States for nominal and perturbed models are available.
- Load the state in HOST working state.
- Calculate the nominal state at time $t + dt$.
- Save the result.
- Load the state of the perturbed model number i in the HOST working state.
- Calculate the state of perturbed model number i at time $t + dt$.

- Save the result and go to time $t + dt$.
- Time $t + dt$: States for nominal and perturbed models are available.

4.3.3 Improvements of the HOST/PID Tool

Some improvements have been introduced to extend the robustness and the performance of the tool:

- Improvement of the second gradient matrix conditioning.

A pseudo-inversion of the $\nabla_2 J$ matrix avoiding the inversion of low eigenvalues is performed.

- Parameter estimation boundaries.

A control of the parameter range is obtained by projecting the direction of research on the maximum or minimum constraints if an estimation exceeds a physical boundary.

- Static characteristic fitting.

The PID algorithm can tune parameters in order to improve the fitting between trim situations calculated and measured. The integration is just replaced by successive equilibrium calculations. In that case all the static data are concatenated in a unique file allocated to a unique set of optimized parameters.

- Estimation of varying parameters.

Only parameters constant versus time or measured information can be directly processed. But a varying physical parameter can be modeled as a polynomial or a spline function. The polynomial or the spline parameters are then able to be optimized by the proposed HOST/PID tool.

4.4 Example of a PID Session

Before the optimization processing the model has to be implemented into the simulation/identification environment. Besides simply embedding the new (parameterized) models into the HOST code, the link of the parameters to the identification module has to be established. Multiple links have to be set in order to take advantage of all the possibilities that HOST offers.

Let us describe the succession of menus, windows and decisions necessary to process in an identification session. The first three menus can be opened with a simple click to go to the following one with the sequence:

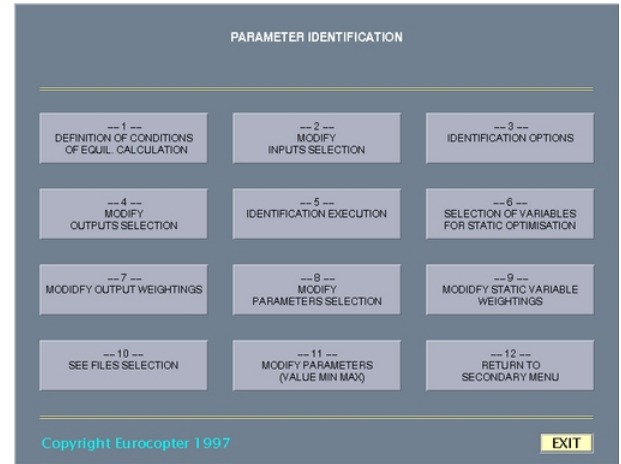


Figure 3: Parameter Identification Menu.

Initial Menu — Calculation Menu — Secondary Menu

In the *Secondary Menu*, select the parameter identification processing to go into the *Parameter Identification Menu* which is now the main menu for the whole identification processing until a click on the *Return to Secondary Menu* button that terminates the identification session. The *Parameter Identification Menu* is depicted in Figure 3.

The buttons listed in Table 2 are available in the present version with the attached functions and selections.

The user is guided by a sequential appearance of each menu. At the beginning of the session, only the buttons 1, 3, 10 and 12 are activated and visible. This is sufficient to define the trim conditions and the general parameters piloting the identification. Nothing more is available before using button 10 to select the SEE-files.

The *Parameter Identification Menu* is recommended to be used as follows

1. Button 10 gives access to a sub menu for the standard selection of the SEE-files. It can provide:
 - a sequential interactive tool to select the dynamic files, the working time ranges and the global weightings of the runs.
 - a selection of a static file and of its measured variables applied to compute the trim components.

At the end of this selection it is possible to go back to the *Parameter Identification Menu*.

2. If dynamic files have been selected, buttons 2 and 4 are available to select the inputs of the model read

Button 1	Trim calculation	Trim definition and calculation.
Button 2	Modify inputs selection	Input of the model read in SEE data files.
Button 3	Identification options	Number of iterations, stop criterion,...
Button 4	Modify outputs selection	Output of the model compared to SEE data files.
Button 5	Identification execution	Estimation algorithm and simulation.
Button 6	Selection of variables for static optimization	
Button 7	Modify output weightings	Standard deviations on output measurements.
Button 8	Identification execution	Estimation algorithm and simulation.
Button 9	Modify static variables weightings	Standard deviations on output measurements.
Button 10	See files selection	
Button 11	Modify parameters	Current, minimum and maximum values of parameters.
Button 12	Return to secondary menu	

Table 2: Identification Buttons and Options.

from the files and the outputs used to build the fitting criterion. If a static file has been selected, button 6 is available to select the variable of the static file to be fitted.

3. Output selection from button 4 activates button 7 which leads to a list of the possible outputs with the standard deviations used to build the fitting criterion. The selected outputs are pointed out by an asterisk and the values can be modified by the user.
4. Static variable selection from button 6 activates button 9 which leads to a list of the possible variables with the standard deviations used to build the fitting criterion.
5. Button 8 is then available to propose a list of the tunable parameters.
6. Button 11 proposes the list of all tunable parameters with the present, minimum and maximum values. The selected parameters to be tuned are pointed out by an asterisk and again the values can be modified by the user.
7. The use of button 5, now activated, starts the identification with warning messages in case of wrong decisions such as missing inputs or outputs. The *zero parameter situation* is accepted, it produces a zero iteration run, i.e. a pure simulation.

The complete menu is now available for further processing and for new sessions just after the SEE-file selection. It is possible to process successive identifications. It may be noticed that the selection operations are decoupled. Then the following parameter estimations can be processed with as few user interactions as possible. It is

only necessary to describe what has been changed with respect to the previous selections. At the end of each identification procedure, the results management of HOST, modified to accept multi-run data, is available to display time histories of flight data and simulations or measured and calculated trim components.

5 Results

The present status of the connection between HOST and the parameter identification codes already provides a tool able to tune some unknown parameters in the models. The user is guided all along the identification session and the decisions, the actions and the provided information are conform to the HOST standard. The identification menu is clearly separated from the other processing and it is easy to:

- Process several identification computations without return to the *standard* menus.
- Alternate standard computations and identifications.

After the implementation of the PWD model, the simulation results already showed a significant improvement with respect to the *bare* Pitt & Peters model (see Figure 4). These computations were conducted with the wake distortion parameters K_p and K_q set to 1.5 equally, according to [10] and [11].

However, as mentioned in Section 3 there are several influences that affect the optimal value of K_p and K_q depending on the flight case. Figure 5 shows the results of a different flight case that underlines the improvements obtained by the optimization of the parameters. For this result, the multi-run option has been used to identify the parameters due to cyclic longitudinal and lateral control

inputs. For flight case #1 (on the left hand side of the vertical lines) the flight test data and simulation allocated to the longitudinal control input flight test are depicted. For flight case #2 (on the right hand side of the lines) the corresponding curves for the lateral input flight test data are shown.

Both, Figure 4 and Figure 5 show the simulation results of a Bo105 helicopter in hover compared to flight test data. As control input, for Figure 4 a cyclic lateral 3 - 2 - 1 - 1 signal and for Figure 5 cyclic longitudinal and lateral doublet signals have been chosen.

For this computation, the wake distortion parameters have been identified with the following values:

$$K_p = 2.3, \quad K_q = 1.7.$$

As one can see, these values are not coincident and do not match exactly the theoretical values listed in Table 1. This may be explained mainly by three reasons:

- Model deficiencies due to simplifications,
- Non-comprised physical effects,
- Non-ideally trimmed flight test data.

General model deficiencies resulting from simplifications that are unavoidable in any modeling task affect the optimization by the attempt of improving the effects of these deficiencies in addition to the actually considered ones. Increased computational performance could reduce these influences but modeling will always comprise simplifications and approximations. Similar to this case the same behavior results from unknown physical effects that are not represented in the model formulation. Here, further research is necessary to discover these effects and to find ways to integrate them into the mathematical modeling. A very practical influence that may affect the simulation and optimization results comes from the quality of flight test data. If not ideally trimmed (i.e. with imposed rotational rates) or disturbed by external or internal inputs that cannot be represented by the simulation, the optimization tends to deal with these effects, too. Only carefully flown flight tests with little, or at least well known external disturbances minimize this kind of negative influence on the optimization result.

Despite a certain influence from these directions the enhancement in simulation fidelity that can be observed improves remarkably the off-axis response prediction — which is, basically, the main goal of the conducted research.

The comparison between Figure 5 and Figure 6 shows the importance of carefully analyzing the model in order to evaluate the results correctly. Both figures show the results of the optimized simulation of the same flight test with identical starting values. The simulation shown in Figure 5 is conducted by pilot control inputs while Figure 6 shows the result of the analysis with swashplate angles as control input.

The difference between these two figures results from the deficiencies of the control chain model between the pilot's cyclic and collective sticks and the swashplate that actually represents the blade root angles and thus the physical system input. Several more or less well known effects are not comprised and the most visible one is represented by the small initial bump in negative direction in the simulated roll response on longitudinal input (around second 22 and 23) in Figure 5 (pilot commands). The simulation depicted in Figure 6 (swashplate commands) does not show this effect which is believed to be allocated to structural flexion of the control booster/swashplate unit.

Consequently to this difference, the identified values for the wake distortion parameters differ from the ones derived for pilot commands:

$$K_p = 2.5, \quad K_q = 1.3.$$

This is a good example to show the impact on the identification of the parameters when the optimization attempts to correct errors that are not allocated to the actual domain of interest, i.e. the wake distortion phenomenon in this case.

Figure 7 shows the effect of optimizing the wake distortion parameters for a horizontal flight of the Bo105 at 80 [kts] with pulse and doublet pilot inputs, the optimized values being:

$$K_p = 1.1, \quad K_q = 1.6.$$

This case also shows a discrepancy to the theory stated in Section 3 which defines the parametric wake distortion as a phenomenon occurring exclusively in/near hover. However, the improving effects are considered to qualify this procedure at least for model tuning purposes.

The results underline the sensitivity of this kind of parametric modeling in nonlinear environment to model uncertainties and ignored physical effects. The attempt to identify the wake distortion parameters contribute to the efforts to numerically assess the complexity of the helicopter rotor wake and its effect on the aircraft's flight dy-

namics. In any case, the optimization functionality improved strongly the simulation accuracy. Next steps in this field will be the evaluation of a permanent embedding of the derived model parameters into the simulation code and to make it accessible to the HOST community.

The next steps in implementing these results are an evaluation of the parameters, e.g. dependent on horizontal speed, allocated to the specific helicopter type and flight state to be permanently implemented into the simulation codes. This could be by a polynomial function similar to the one presently in use but with optimized values.

6 Conclusions and Outlook

The identification tool extends the capabilities of the HOST system significantly. A variety of problems can be treated that require a parametric modeling in order to optimize the predicted behavior of the aircraft. A further development is planned including following improvements which are considered to enhance the performance of the tool further:

- Mixed static and dynamic optimizations have to be performed.
- Varying parameters have to be taken into account.
- Further testing at DLR, ONERA and Eurocopter will contribute to the code consolidation.
- The user friendliness of this interactive tool will be further improved by the work shared between DLR and ONERA.

For the test case described above, the optimization of the parametric wake distortion (PWD) model generated results that improved the insight in various aspects of the performed analysis. The characteristics of the modeling approach become more clear.

The optimization of the PWD model led to strong improvements in helicopter response prediction which allows to optimistically step forward towards new applications and, finally, the systematic integration as a common method of modeling.

Presently, various applications are planned such as the identification of a modified Fenestron model and a parametric engine model in a real-time simulation environment.

Lately, various efforts have been made to improve the dynamic response prediction of helicopter models that are

equipped with the Fenestron anti-torque system [19]. Different approaches lead to an improvement but deficiencies are still remaining. It is intended to set up an extended model that consists of the standard formulation plus a parametric *error model*, i.e. a term that is supposed to represent the deficiencies in the dynamic response. After the optimization of the parameters a significant improvement is expected that can constantly be integrated into the model code.

Since no detailed information on the engine that will be installed on the EC135 ACT/FHS demonstrator is available until the aircraft becomes operational, the dynamic engine model developed for the Bo105 real-time simulation [14] was integrated into the new EC135 formulation by adapting the RPM governor parameters to represent the FADEC response characteristics. Despite the successful adaption of the model to the new helicopter type there are still model deficiencies in the prediction of the dynamic behavior of the engine (e.g. the reaction in rotor RPM to pedal or collective input). Compared to the parametric wake distortion model where one of the difficulties is to optimize a local (wake) problem by the use of global system input (cyclic stick/swashplate) an output (roll and pitch rate), the FADEC system allows to work specifically with the variables allocated directly to the phenomenon that is being analyzed. It is now aimed to convert the model into a form that is accessible for the parameter optimization. With the flight test data that will be available from the ACT/FHS FADEC system it will be possible to improve the model in a way that it covers the needs for dynamic behavior prediction satisfactorily.

There are many challenging projects where this integrated combination of a simulation tool and a parametric identification procedure can be of good use to generate simulations that provide improved fidelity along with a large spectrum of application — a consequence of the strategy of using nonlinear modeling extended by parametric approaches to guard a maximum of physical accuracy along with improved simulation fidelity. For future application it is planned to use the described codes as permanent optimization tool and to increasingly use this basis of model improvement.

Acknowledgement

The French part of this work was supported by the French Ministry of Defense.

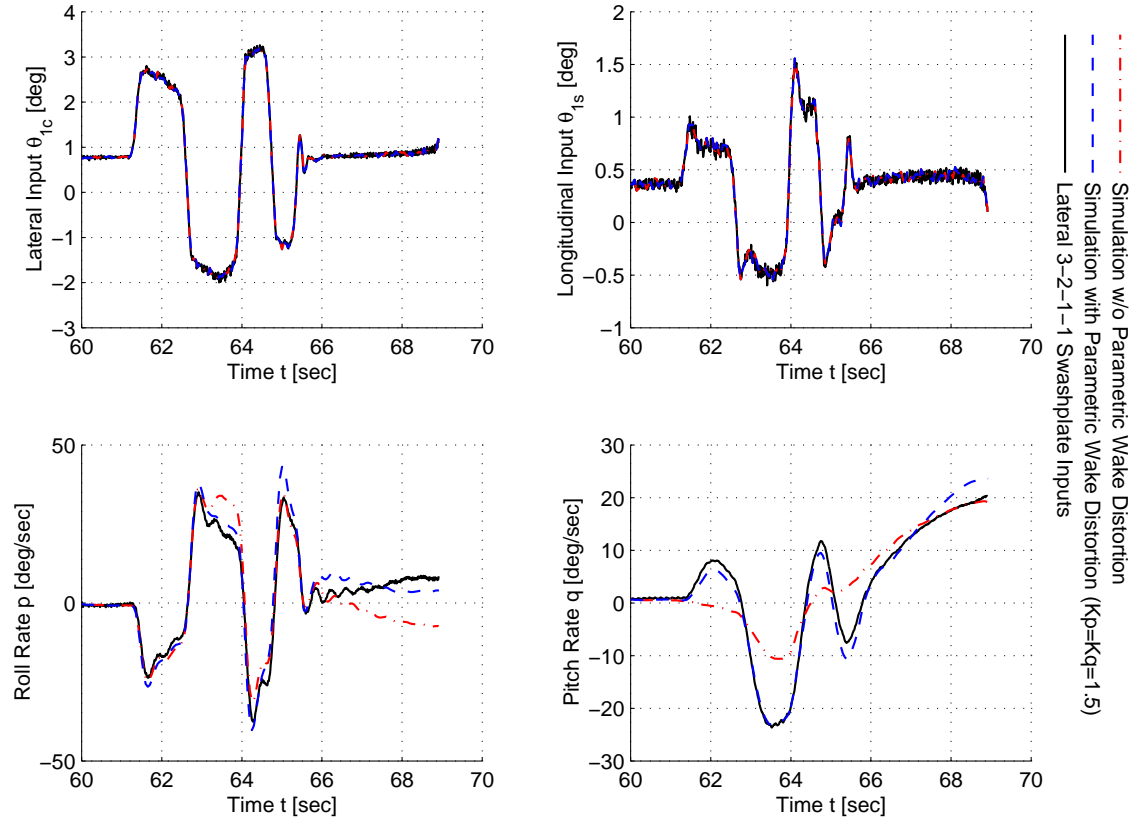


Figure 4: Comparison of the simulations with and without the PWD model.

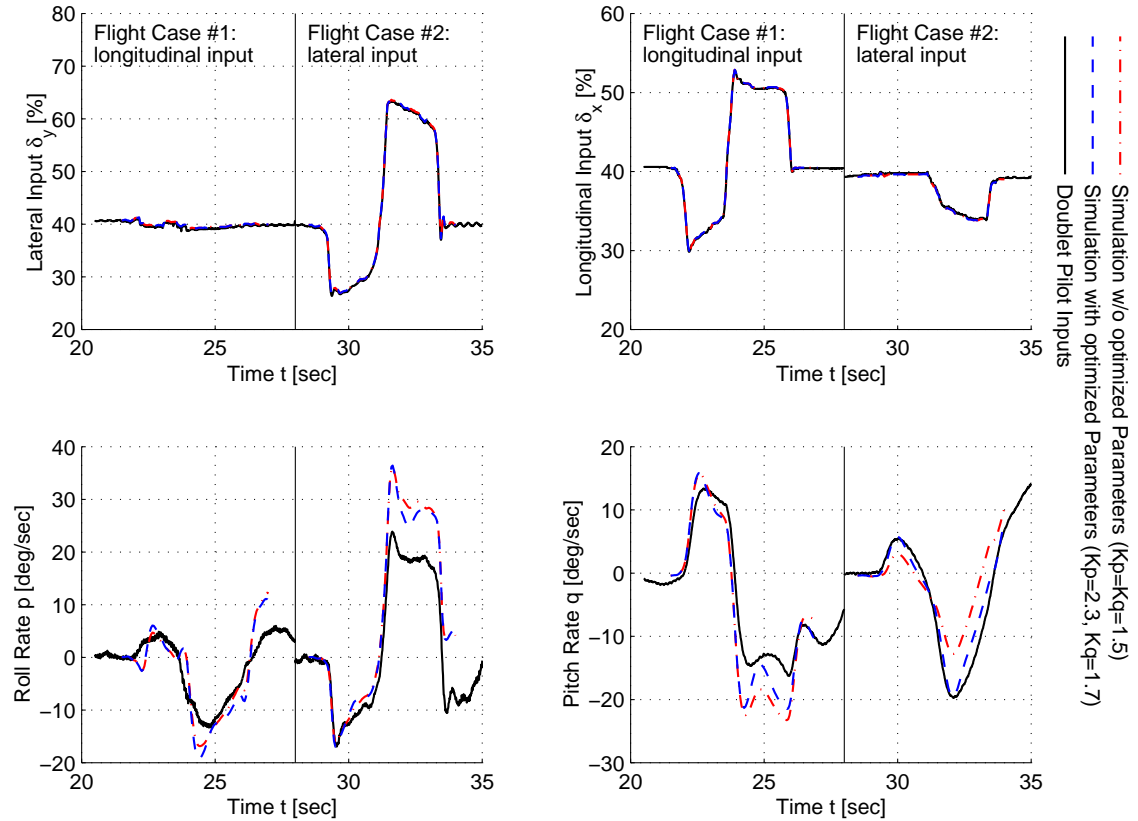


Figure 5: Comparison of the simulations with optimized and non-optimized PWD in hover — Pilot commands.

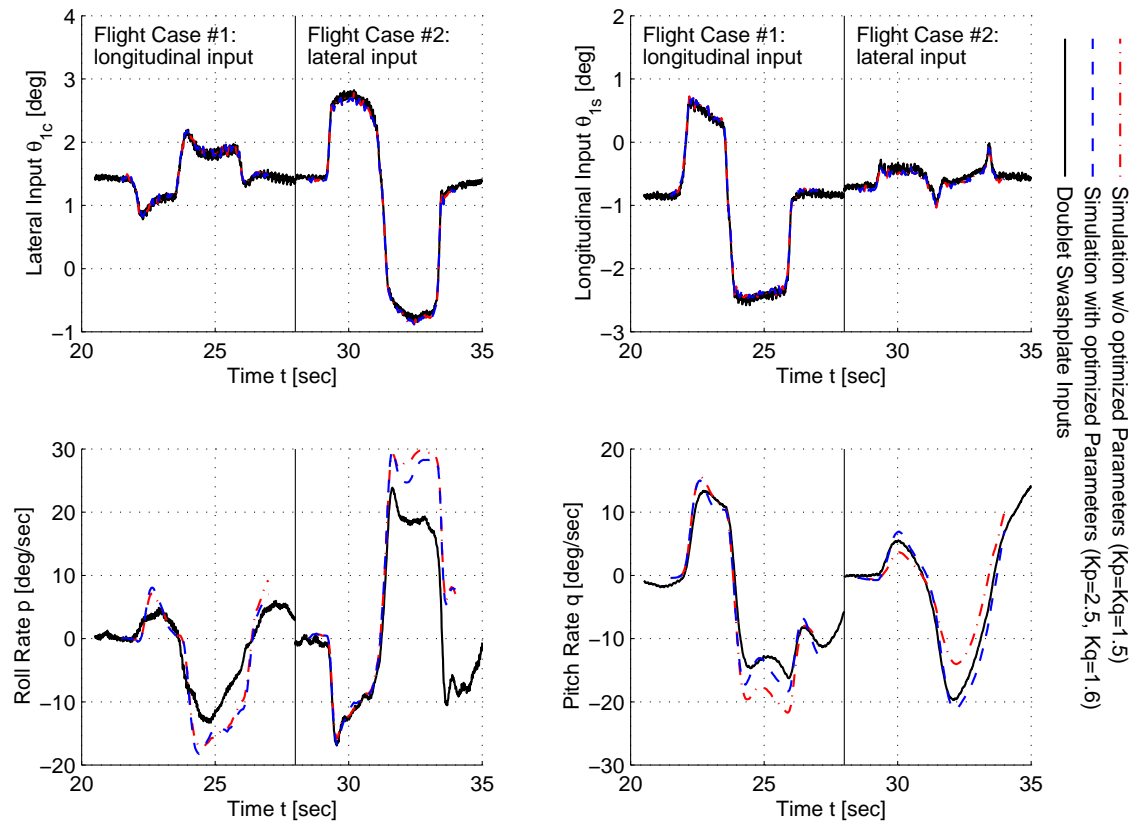


Figure 6: Comparison of the simulations with optimized and non-optimized PWD in hover — Swashplate commands.

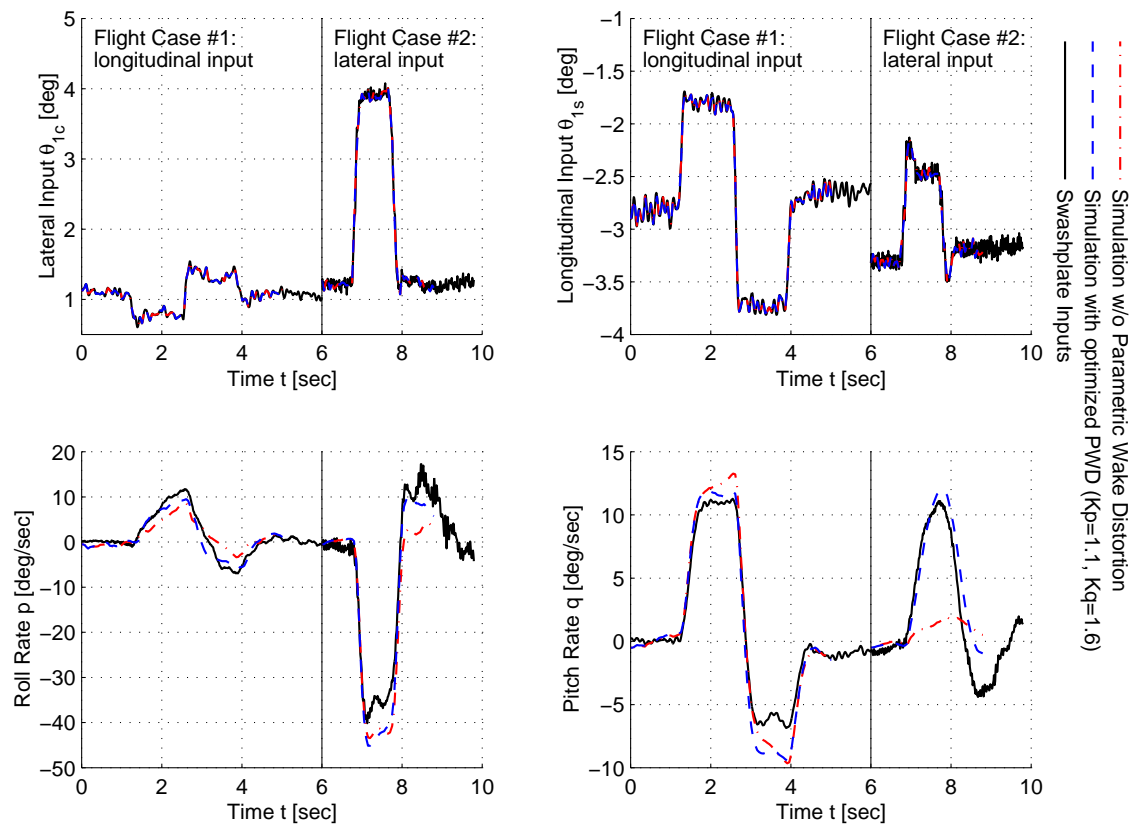


Figure 7: Comparison of the simulations with optimized and non-optimized PWD parameters in level flight.

References

- [1] W. v. Grünhagen, G. Bouwer, H.-J. Pausder, F. Henschel, J. Kaletka: *A high bandwidth control system for the helicopter in-flight simulator ATTheS — modelling, performance and applications*, Published in the book "Advances in Aircraft Flight Control", edited by M. B. Tischler, Taylor & Francis Ltd., UK, 1996.
- [2] M. Hamers, G. Bouwer, W. v. Grünhagen: *System Simulator for the DLR's Inflight Simulator ACT/FHS — Software and Hardware Realisation*, AHS Vertical Lift Aircraft Design Conference, San Francisco, CA, 2000.
- [3] A. Rosen, A. Isser: *A new Model of Rotor Dynamics during Pitch and Roll of a Hovering Rotor*, AHS 50th Annual Forum, Washington, DC, 1994.
- [4] J.D. Keller, H.C. Curtiss: *Modeling the Induced Velocity of a Maneuvering Helicopter*, AHS 52nd Annual Forum, Washington, DC, 1996.
- [5] M. Hamers, W. v. Grünhagen: *Nonlinear Helicopter Model Validation Applied to Realtime Simulations*, AHS 53rd Annual Forum, Virginia Beach, VA, 1997.
- [6] P.-M. Basset, F. Tchen-Fo: *Study of the Rotor Wake Distortion Effects on the Helicopter Pitch-Roll Cross-couplings*, 24th European Rotorcraft Forum, Marseilles, France, 1998.
- [7] M. Rohlf, W. v. Grünhagen, J. Kaletka: *Nonlinear Rotorcraft Modeling and Identification*, RTO SCI Symposium on "System Identification for Integrated Aircraft Development and Flight Testing", Madrid, Spain, 1998.
- [8] P.G. Hamel et al.: *Rotorcraft System Identification*, AGARD Lecture Series LS 178, Specialised Printing Services Ltd., UK, 1991.
- [9] D.M. Pitt, D.A. Peters: *Theoretical Prediction of Dynamic Inflow Derivatives*, 6th European Rotorcraft Forum, Bristol, England, 1980.
- [10] J.D. Keller: *An Investigation of Helicopter Dynamic Coupling using an Analytical Model*, 21st European Rotorcraft Forum, St. Petersburg, Russia, 1995.
- [11] P.-M. Basset: *Modeling of the Dynamic Inflow on the Main Rotor and the Tail Components in Helicopter Flight Mechanics*, 22nd European Rotorcraft Forum, Brighton, England, 1996.
- [12] E. Barocela, D.A. Peters, K.R. Krothapalli, J.V.R. Prasad: *The Effect of Wake Distortion on Rotor Inflow Gradients and Off-Axis Coupling*, AIAA-97-3579, 1997.
- [13] A. Bagai, J.G. Leishman, J. Park: *A Free Vortex Rotor Wake Model for Maneuvering Flight*, AHS Technical Specialists Meeting for Rotorcraft Acoustics and Aerodynamics, Williamsburg, VA, 1997.
- [14] M. Hamers, W. v. Grünhagen: *Dynamic Engine Model integrated in Helicopter Simulation*, 23rd European Rotorcraft Forum, Dresden, Germany, 1997.
- [15] Eurocopter: *Helicopter Overall Simulation Tool*, General Documentation, Marignane, France, 1994-1998.
- [16] B. Benoit, A.-M. Déquin, K. Kampa, W. v. Grünhagen, P.-M. Basset, B. Gimonet: *HOST, a General Helicopter Simulation Tool for Germany and France*, AHS 56th Annual Forum, Virginia Beach, VA, 2000.
- [17] B. Gimonet, J. Kaletka: *DLR-ONERA Cooperation on SMART Helicopter Concept*, Status Report on Task 1.3, Helicopter System Identification, Toulouse, France, 1994.
- [18] Ph. Krämer, B. Gimonet, W. v. Grünhagen: *Model Parameter Estimation with HOST (Helicopter Overall Simulation Tool)*, 2nd ONERA-DLR Aerospace Symposium, Berlin, Germany, 2000.
- [19] A. Jaeken, W. v. Grünhagen: *Investigation of Feneutron Modelisation in HOST*, DLR internal report, IB-111-2000/15, Braunschweig, Germany, 2000.